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Analysis of Effect of Flameholder Characteristics on Lean, Premixed, Partially Vaporized Fuel-Air Mixture Quality and Nitrogen Oxides Emissions

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Summary

An analysis has been conducted of the effect of flameholding devices on precombustion fuel-air mixture characteristics and on oxides of nitrogen (NO_x) emissions for combustion of premixed, partially vaporized mixtures.

The analysis of the effect on mixture quality of the flameholding device has resulted in a formulation which includes the interrelationships between the flameholder droplet collection efficiency, reatomization efficiency and blockage, and the initial droplet size distribution. The analysis of the combustion of premixed, partially vaporized mixtures has yielded a procedure to account for the contribution of droplet combustion in partially vaporized mixtures to the NO_x emissions.

The procedures developed in this analysis can be used to predict the nitrogen oxide emissions from lean, premixed, partially vaporized mixtures. This calculation requires that combustor conditions of temperature, pressure, fuel type, equivalence ratio, and residence time be known and that the initial fuel-air preparation characteristics (e.g., droplet size distribution, and degree of vaporization) be known from either measurement or calculation. In addition, the interrelationship of the flameholder collection, reatomization, and blockage must be known from either measurement or calculation. Application of the analytical procedures is illustrated and parametric predictions of NO_x emissions are presented.

Introduction

This paper reports an analysis of the effect of flameholder characteristics of blockage, liquid collection, and reatomization on the precombustion fuel-air mixture characteristics and on nitrogen oxides (NO_x) emissions for combustion of premixed, partially vaporized mixtures.

Increasing demands are being placed on combustion systems as a result of escalating costs for fuel and maintenance as well as of regulations governing the permissible levels of exhaust-gas pollutants. Several studies (refs. 1 to 4) have explored methods of advancing combustor technology to meet these demands. A combustion technique that has been identified as a potential method of obtaining superior performance, high durability, fuel flexibility, and low pollutant emissions is premixed-prevaporized combustion at lean equivalence ratios.

Previous studies (refs. 5 to 6) of lean premixed-prevaporized (LPP) combustion have shown that the flameholder represents an important design element of such systems. The combustion process is stabilized by recirculation zones generated by the flameholder. Factors such as flameholder blockage and geometry affect the recirculation zone characteristics and hence the combustion stability, emissions, and performance.

The previous studies (refs. 5 to 6) have been limited to experiments using fully premixed, prevaporized mixtures in which the fuel was completely vaporized and well mixed with air before combustion. Numerous flametube studies (refs. 7 to 12) have indicated that optimum performance and emissions are obtained with these fully premixed, prevaporized mixtures. However, in the application of the lean, premixed, prevaporized approach to aircraft gas turbines, it may not be feasible to obtain this ideal condition because at some operating points the fuel-air mixture may become chemically reactive and autoignite before completely vaporizing.

Under conditions where the fuel-air mixture is not completely vaporized, a flameholding device can affect the mixture quality as well as the combustion process. Depending on the design of the flameholder and the fuel preparation section, fuel droplets can impact the flameholder and subsequently be reatomized, thus altering the characteristics of the fuel-air mixture.

This influence of the flameholding device on mixture quality was found to be important in a previous study (ref. 13) of the effect of fuel-air mixture characteristics on emissions for LPP combustion. In this previous study an analytical model for the combustion of partially vaporized mixtures was formulated, and emissions of nitrogen oxides were postulated to be due to a contribution of vapor-phase combustion and droplet combustion at stoichiometric conditions. The predictions of the model were found to agree with experimental results if impaction and reatomization of liquid fuel droplets by the flameholder were included in the data analysis.

The objective of the analysis reported herein was to analytically investigate the effect that flameholder devices could have on fuel preparation quality and on

the subsequent emissions for premixed, partially vaporized mixtures of liquid fuel and air. The analysis previously formulated in reference 13 was expanded to take into account the potential differences in the blockage, liquid collection, and reatomization characteristics of flameholders. This expanded analysis was used to parametrically examine the effect that flameholding devices could have on fuel preparation quality and the NO_x emissions from the combustion of partially vaporized mixtures.

Flameholding Devices in Premixed Partially Vaporized Flows

Application of the lean, premixed, prevaporized combustion approach to aircraft gas turbines requires limits on the time available for liquid-fuel vaporization in order to avoid the possibility that the fuel-air mixture could become chemically reactive and autoignite in the premixing duct ahead of the flameholding device. Unless the fuel vaporization can be accomplished within this limited time, the flameholding device will be presented with premixed, partially vaporized flows.

The basic function of the flameholding device in premixed, prevaporized combustion is to provide a sheltered region with sufficient residence time that a stable combustion zone can be established. The fuel and air within this recirculation zone react to produce high-temperature radical-carrying gases which are mixed into the remaining fuel and air mixture to complete the combustion process.

Flameholding devices have been studied by numerous investigators (refs. 14 to 17) to determine the factors that influence the ability of the device to produce stable combustion and their pollutant emission levels. It has been found that fuel type, fuel-air ratio, velocity, temperature, pressure, and flameholder size, shape, and blockage are the principle controlling factors relative to flameholding devices in premixed-prevaporized flows.

Figure 1 is an illustration of a flameholding device in a premixed, partially vaporized flow. As illustrated in this figure, the flameholding device can alter the premixed, partially vaporized flow as droplets impact the flameholder surface, are collected into a fuel film, and are then reatomized at

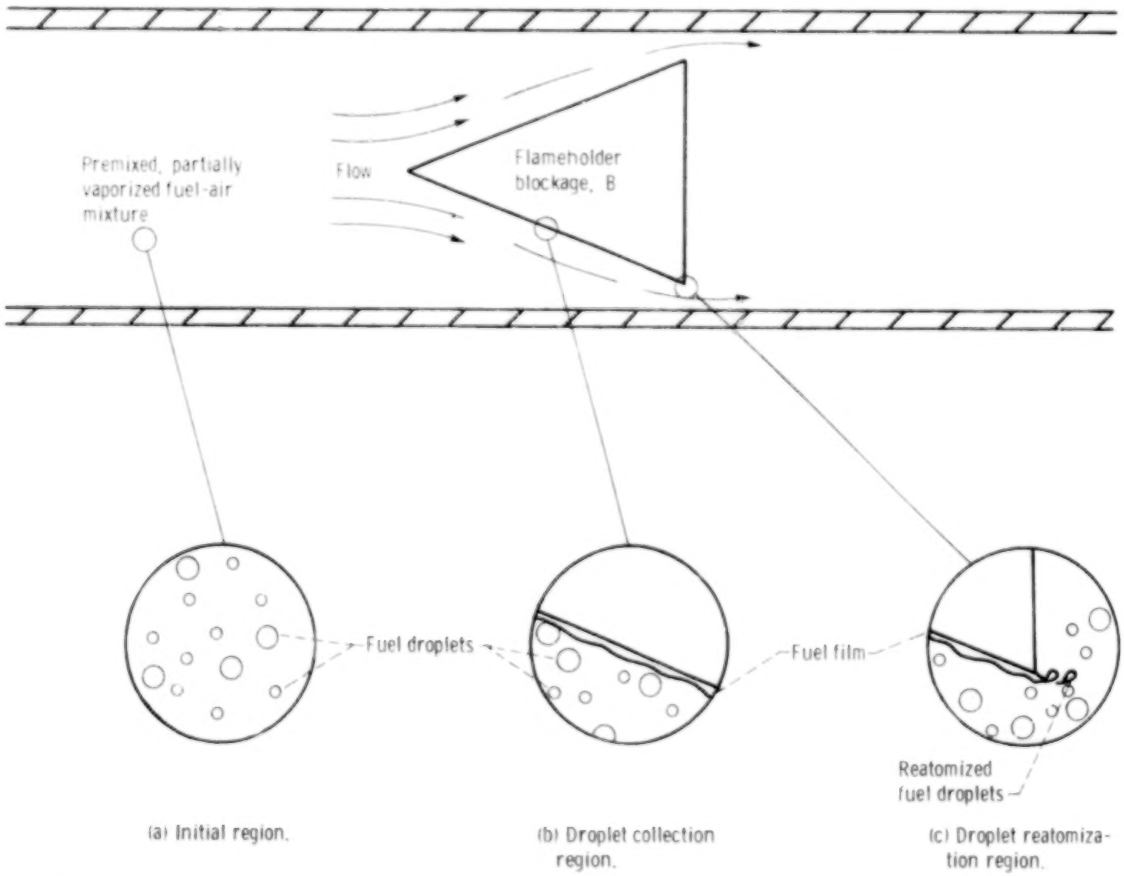


Figure 1. - Flameholder in premixed, partially vaporized flow illustrating liquid droplet collection and reatomization phenomena.

the lip of the flameholding device. Thus, the factors of droplet size distribution, degree of fuel vaporization, droplet collection, and reatomization are added to the list of variables affecting the emissions and stability of flameholding devices in premixed, partially vaporized flows.

Analysis

As discussed in the previous section, Flameholding Devices in Premixed Partially Vaporized Flows, the application of lean premixed, prevaporized combustion to aircraft gas turbines may entail the burning, at certain times, of fuel and air mixtures in which the fuel is only partially vaporized.

In this section analytical expressions are proposed to account for the influence of a flameholding device upon mixture quality and upon oxides of nitrogen emissions from the combustion of premixed partially vaporized mixtures.

Nitrogen Oxides Emissions

In reference 13 a mechanism was proposed to account for the effect of partially vaporized mixtures on emissions of oxides of nitrogen (NO_x). The mechanism was based on observations of several investigators (refs. 18 to 21) of droplets being consumed by diffusion flames in partially vaporized mixtures and on the rationale that the combustion of liquid droplets, as well as vapor phase burning, will contribute to the total NO_x emissions.

For mixtures that are composed of mostly vapor, the effect of these droplets upon the combustion process can be viewed as a perturbation to the vapor phase mechanism. The total NO_x produced by the liquid droplets burning can then be considered in addition to the vapor combustion contribution. Thus, total NO_x on an emission index basis for a partially vaporized mixture can be separated as

$$(NO_x)_{tot} = E_t\,(NO_x)_{\text{vapor burning}} + (1 - E_t)(NO_x)_{\text{droplet burning}} \quad (1)$$

where E_t is the fraction of the fuel in the vapor state and $(1 - E_t)$ the fraction of fuel in the liquid droplet state.

Investigators (refs. 19 and 22) have found that the droplet size distribution plays a role in the droplet combustion process. It has been found that a critical drop size diameter range exists, that droplets above this size range are consumed by the classical diffusion flame mechanism, and that droplets below this size range are consumed in a nature similar to a true vapor. Oxides of nitrogren emissions for these droplets have been found to be equivalent to those of a vapor fuel at the same overall equivalence ratio. Thus, the NO_x contribution from droplet burning can be further separated as

$$(1 - E_t)(NO_x)_{\text{droplet burning}} = F(1 - E_t)(NO_x)_{\phi = 1} + (1 - F)(1 - E_t)(NO_x)_{\phi_t} \quad (2)$$

where F is the fraction of the fuel droplets that are consumed by the diffusion flame mechanism to produce oxides of nitrogen at stoichiometric conditions, $(NO_x)_{\phi = 1}$. The remainder of the droplets burn as pseudovapor and produce oxides of nitrogen as a vapor would at the pseudovapor phase equivalence ratio, ϕ_t.

The contribution of the pseudovapor fraction can be included with the true vapor fraction and the total oxides of nitrogen emissions expressed as

$$\begin{aligned}(NO_x)_{tot} &= E_t + (1 - F)(1 - E_t)\,(NO_x)_{\phi_t} + F(1 - E_t)(NO_x)_{\phi = 1} \\ &= E_t'(NO_x)_{\phi_t} + E_{DCR}(NO_x)_{\phi = 1} \\ &= (1 - E_{DCR})(NO_x)_{\phi_t} + E_{DCR}(NO_x)_{\phi = 1} \end{aligned} \quad (3)$$

Thus, the total oxides of nitrogen emissions depend directly on the final mixture droplet fraction greater than the critical diameter, E_{DCR}, and the total fuel vapor fraction, E_t' (pseudovapor fraction plus the true vapor fraction).

Emissions of oxides of nitrogen have been found to be strongly influenced by both the equivalence ratio and the combustor entrance conditions. The adiabatic flame temperature, which is itself a function of these quantities,has been found to be a useful correlation parameter for NO_x (refs. 10 and 23)

For partially vaporized mixtures the vapor phase adiabatic flame temperature T_v is a function of the pseudovapor phase equivalence ratio, ϕ_t, which is a function of the fuel vapor fraction, E_t, the pseudovapor fraction, $(1 - F)(1 - E_t)$, and the overall equivalence ratio; that is

$$\phi_t = [E_t + (1 - F)(1 - E_t)]\,\phi = E_t'\phi \quad (4)$$

From a knowledge of these quantities, it is possible to determine the vapor phase adiabatic flame temperature, T_v, and the corresponding NO_x emissions by using either published experimental data (refs. 8, 10, and 23) or an analytic model (refs. 24 to 25) for combustion in a stirred reactor, an

approach which has been found to be applicable to lean, premixed, prevaporized combustion processes.

Combustion of droplets above the critical size range has been found to be by a diffusion flame mechanism at stoichiometric conditions with corresponding high temperatures which produce large quantities of NO_x (refs. 20 to 22). Thus, it may be assumed that NO_x produced by droplet combustion can be estimated from the adiabatic flame temperature T_1, which corresponds to stoichiometric conditions at the combustor inlet conditions.

Based on this analysis, the effect of the fuel vapor fraction (true vapor + pseudovapor on the total NO_x emissions over a range of inlet temperatures and overall equivalence ratios has been previously calculated for Jet A fuel (ref. 13). The analytical results from that study are listed in table I and shown in figure 2. They were computed from equation (3) with NO_x emission indices from a stirred reactor model (ref. 24).

Figure 2(a) shows the calculated effect of fuel vapor fraction on the total NO_x emissions for fixed residence time, inlet pressure, and overall equivalence ratio over a range of inlet temperatures. The total NO_x emissions decrease with decreasing inlet temperature. This would be expected since NO_x correlates with adiabatic flame temperature, which itself decreases with decreasing inlet temperature.

Figure 2(b) shows the effect of fuel vapor fraction on the total NO_x emission for fixed residence time, inlet pressure, and temperature over a range of overall equivalence ratios. The total NO_x emissions decrease with decreasing overall equivalence ratio. A result expected since the adiabatic flame temperature decreases with decreasing overall equivalence ratio.

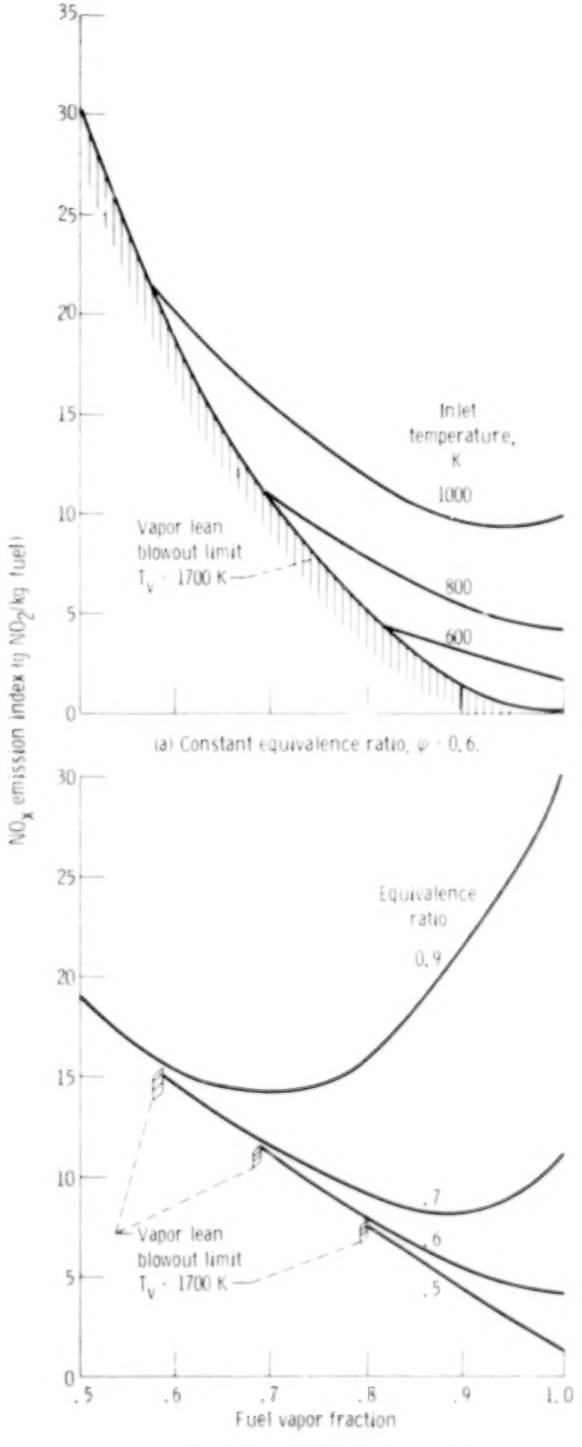
TABLE I. - EFFECT OF FUEL VAPOR FRACTION ON NITROGEN OXIDES EMISSION INDEX OVER A RANGE OF INLET TEMPERATURES AND EQUIVALENCE RATIOS[a]

[Inlet pressure, 10 atm; residence time, 2 msec., Jet A fuel.]

Overall equivalence ratio, θ	Fuel vapor fraction, E_v	Vapor phase equivalence ratio, θ_v	Inlet temperature, K					
			600		800		1000	
			Vapor phase flame temperature, T_v, K	NO_x emission index, g NO_2/kg fuel	Vapor phase flame temperature, T_v, K	NO_x emission index, g NO_2/kg fuel	Vapor phase flame temperature, T_v, K	NO_x emission index, g NO_2/kg fuel
0.5	0.70	0.35	-----	---	[b]1630	-----	----	----
	.80	.40	-----	---	1700	7.40	----	----
	.90	.45	-----	---	1785	4.25	----	----
	1.00	.50	-----	---	1910	1.40	----	----
0.6	0.60	0.36	[b]1420	---	[b]1620	-----	1750	20.0
	.70	.42	[b]1590	---	1750	11.0	1895	16.0
	.80	.48	1700	4.4	1870	8.0	2006	12.0
	.90	.54	1810	2.9	1980	5.3	2115	9.0
	1.00	.60	1920	1.6	2090	4.25	2225	10.0
0.7	0.60	0.42	-----	---	1750	14.4	----	----
	.70	.49	-----	---	1865	11.4	----	----
	.80	.56	-----	---	2010	9.1	----	----
	.90	.63	-----	---	2115	8.0	----	----
	1.00	.70	-----	---	2285	11.0	----	----
0.9	0.50	0.45	-----	---	1810	19.0	----	----
	.60	.54	-----	---	1965	15.2	----	----
	.70	.63	-----	---	2130	14.4	----	----
	.80	.72	-----	---	2255	15.8	----	----
	.90	.81	-----	---	2370	21.5	----	----
	1.00	.90	-----	---	2480	30.0	----	----

[a]Ref. 13.

[b]Below lean blowout limit of 1700 K (ref. 10).



(a) Constant equivalence ratio, φ = 0.6.

(b) Constant inlet temperature, 800 K.

Figure 2. - Effect of fuel vapor fraction on nitrogen oxide emission index over a range of inlet temperatures and equivalence ratios. Inlet pressure, 1 MPa; residence time, 2 milliseconds. (From ref. 13.)

In figure 2(b) note that a minimum exists in the toal NO_x emissions for overall equivalence ratios of 0.7 and 0.9. The reason for this minimum is the tradeoff which exists between reductions in the vapor phase equivalence ratio to reduce the vapor phase NO_x contribution and a corresponding increase in the liquid fraction which increases the NO_x contribution for liquid droplet burning. The NO_x emissions initially decrease with decreasing fuel vapor fraction, E_v. The reduction in the vapor phase equivalence ratio dominates since the liquid droplet fraction contribution is initially small. A balance point is reached between the vapor phase and droplet fraction NO_x contributions which minimizes NO_x. NO_x then increases with decreasing vapor fraction (increasing droplet fraction) as the droplet fraction dominates.

Based on the results given in table I, the following behavior may be noted in terms of the vapor phase adiabatic flame temperature, T_f. For a given inlet temperature and overall equivalence ratio:

(1) When T_f falls below 2050 K, decreases in the fuel vapor fraction will result in an increase in the total NO_x emissions. (Liquid droplet fraction combustion contribution dominates.)

(2) If T_f is between 2050 and 2200 K, decreases in the fuel vapor fraction will have little effect on total NO_x. (Liquid droplet fraction combustion and vapor phase combustion contributions balance.)

(3) If T_f is above 2200 K, decreases in the fuel-vapor fraction will result in a decrease in NO_x emissions. (Vapor phase combustion contribution of NO_x dominates.)

The minimum NO_x emission occurs at the fuel vapor fraction that corresponds to a vapor phase adiabatic flame temperature of approximately 2100 K. Mixtures for which the vapor phase adiabatic flame temperature is always below 2100 K have their minimum at complete fuel vaporization.

The system behavior and temperature ranges discussed above are specific to Jet A fuel. It is beyond the scope of this report to explore the effect of fuel type on NO_x emissions for lean, premixed, partially vaporized mixtures. Other fuels will have different temperature characteristics and system behaviors as a result of their specific chemical kinetics. In particular those fuels having high levels of fuel bound organic nitrogen will probably differ substantially since the level of conversion of the fuel-bound organic nitrogen must also be accounted for.

For given inlet conditions and combustor geometry, the lean stability limit is the lowest overall equivalence ratio that will support combustion. As shown in table I and marked in figure 2, the lean stability limit for Jet A fuel has been assumed to be the point when the vapor phase adiabatic flame temperature is less than 1700 K. This value is based

on the results (ref. 10) of flametube studies of prevaporized fuels. Lean stability limits for partially vaporized mixtures tend to be lower than those of fully vaporized mixtures and depend on droplet size number and distribution (refs. 18 to 22). These factors are dependent on the particular combustion system being studied.

Mixture Quality

Mixture quality of premixed, partially vaporized fuel and air mixtures is composed of the mixture's degree of fuel vaporization and the mixure's droplet size distribution. Since fuel droplets in a partially vaporized mixture can impact a flameholding device, be captured, and subsequently be reatomized, the flameholding device can influence the quality of the mixture which ultimately undergoes combustion.

As shown previously, the NO_x emission from the combustion of partially vaporized mixtures is directly related to the mixture droplet fraction greater than the critical drop diameter, E_{DCR}, and to the remaining fraction, composed of the vaporized fuel and of the droplet fraction, less than the critical diameter (pseudovapor). To determine the final droplet fraction, E_{DCR}, it is necessary to examine and quantify how the flameholding device can interact with an initial mixture of air, vaporized fuel, and fuel droplets.

Referring to figure 1, as the mixture of vaporized fuel, air, and fuel droplets flows toward the flameholding device the gas is accelerated in order to pass through the reduced cross sectional area at the flameholding device. The fuel droplets are acted upon by the drag forces resulting from the changing flow field and attempt to follow the flow streamlines through the flameholding device. Depending on the droplet size, and on the magnitude of the drag forces, droplets may be unable to follow the streamlines through the flameholding device and impact its surface. These droplets form a liquid fuel film which is drawn over the flameholding device by the liquid surface tension and gas flow and the film is then reatomized at the lip of the flameholding device. This process results in a droplet size distribution of reatomized droplets.

The final mixture droplet fraction, E_d, is thus composed of distinct components: (1) Those droplets from the initial mixture that pass through the open area of the flameholder and (2) those droplets that result from the reatomization of the liquid film from the droplets impacting the flameholding device.

The final total droplet fraction can be expressed as:

$$E_d = \begin{pmatrix}\text{portion of initial droplet fraction}\\ \text{which passes through open area of}\\ \text{flameholding device}\end{pmatrix} + \begin{pmatrix}\text{portion of initial droplet fraction}\\ \text{which impacts the flameholding}\\ \text{device and is reatomized}\end{pmatrix}$$

$$= (1 - E_t)(1 - C) + (1 - E_t)C$$

$$= (1 - E_t) \tag{5}$$

where E_t is the initial fraction of vaporized fuel, $(1 - E_t)$ is the initial fraction of fuel droplets, and C is a capture factor. Note that since all the droplets that impact and are captured by the flameholder are subsequently reatomized, the final total droplet fraction is the same as the initial fraction of fuel droplets.

The capture factor for a flameholding device in a premixed, partially vaporized flow is representative of the fraction of droplets in the mixture that impact the device. Referring to figure 1, the only droplets that can impact are those that fall within the flameholders maxium cross sectional area or capture area. Thus, the capture factor can be expressed as

$$C = \frac{B}{100} K \tag{6}$$

where B is the flameholding device blockage in percent and K is the collection efficiency. The collection efficiency can range from zero, when all the droplets are able to follow the flow streamlines and avoid impacting the device, to unity, when all the droplets within the area defined by the flameholding device maximum cross sectional area, impact the device and are captured. Factors such as the droplet size distribution and the flow field aerodynamics, as established by the flameholding device's geometry, will determine what fraction of the droplets are ultimately collected. Analytical models can be used to compute the collection factor when the geometry, inlet conditions, and droplet characteristics are known.

The final mixture droplet fraction greater than the critical diameter, E_{DCR}, can be determined by a similar approach to that of the final droplet fraction E_D, that is,

$$E_{DCR} = \begin{pmatrix}\text{portion of initial droplet fraction greater than critical diameter which passes through open area of flameholding device}\end{pmatrix} + \begin{pmatrix}\text{portion of initial droplet fraction which impacts the flameholding device and is reatomized to droplets greater than the critical diameter}\end{pmatrix}$$

$$= M(1 - E_t)\left(1 - \frac{B}{100}K\right) + (1 - E_t)\left(\frac{B}{100}K\right)(1 - N)$$

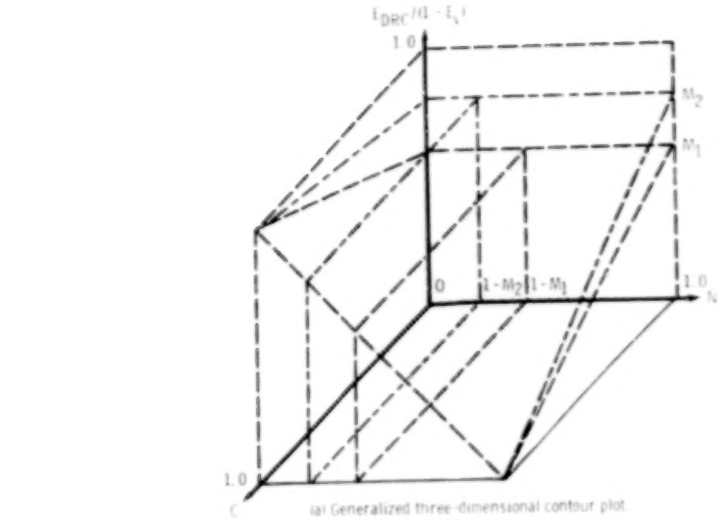
$$= M(1 - E_t)(1 - C) + (1 - E_t)C(1 - N) \qquad (7)$$

where M is the fraction of the initial droplets greater than the critical diameter and $(1 - N)$ is the portion of the collected fuel droplets which are reatomized into droplets greater than the critical diameter. The reatomization efficiency, N, represents the system's ability to reatomize a collected liquid film into droplets less than the critical diameter. Its value can range from zero, when all the reatomized droplets are greater than the critical diameter, to unity, when all the reatomized droplets are less than the critical diameter. Factors such as the film thickness, fuel properties of viscosity and surface tension, and air velocity will all influence the size distribution of the reatomized droplets. The film thickness is directly related to the amount of liquid collected and so the factors of droplet size, flameholder blockage, and flow field aerodynamics which influence the collection factor will also affect the reatomization efficiency and the reatomized size distribution.

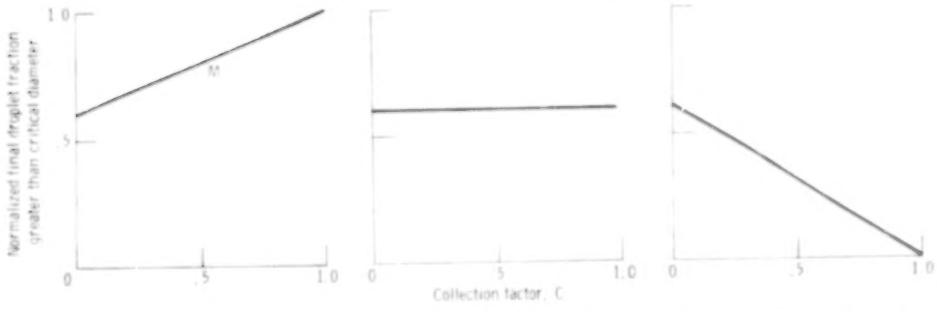
At present, there are only limited data on which to base computations of reatomization efficiency (refs. 26 to 27). These data are from studies have been conducted at conditions of low temperature and pressure with uniform film thickness. The measurements have beem limited to the droplet size Sauter mean diameter. As such, only estimates of the actual drop size distribution can be made at higher temperatures and pressures of the advanced gas turbine.

The portion of droplets greater than the critical diameter, E_{DCR}, can be greater than, equal to, or less than the initial droplet fraction greater than the critical diameter $(1 - E_t)$ depending on the values of the capture factor, C, and the reatomization efficiency, N. Normalizing the final droplet fraction greater than the critical diameter by the initial droplet fraction, $(1 - E_t)$, permits a graphical representation of the interrelation between the variables to be expressed as contour plots as shown in figure 3. Shown in figure 3(a) is the three-dimensional contour plot which illustrates the potential values that can be assumed by the normalized final droplet fraction greater than the critical diameter. The premissible values are confined to a plane determined by the reatomization efficiency, N, collection factor, C, and the droplet fraction initially greater than the critical diameter, M. As shown, the location of the plane varies with changing values of M. This contour plot illustrates the limits which are placed on the system. Only a limited set of values can be obtained when two of the variables are selected. For example, with fixed values of reatomization efficiency and initial droplet fraction greater than the critical diameter, only a limited variation can be obtained in the normalized final droplet fraction greater than the critical diameter by varying the flameholder collection factor.

The two-dimensional contour plots shown in figure 3(b) to (d) are sectional views of the three-dimensional contour plot of figure 3(a). As shown, the normalized final droplet fraction greater than the critical diameter can increase, decrease, or remain unchanged with changing capture factor, depending on the reatomization efficiency. When the atomization efficiency is high (greater than $1 - M$), most of the captured droplets impacting the flameholder are reatomized into droplets that are less than the critical diamter. Thus, a portion of the droplets that were initially greater than the critical diameter are converted to droplets less than the critical diameter by being collected and reatomized by the flameholding device. As the capture factor increases, a greater fraction of these droplets are captured and reatomized. Thus, the normalized final droplet fraction greater than the critical diameter decreases. Conversely, when the reatomization efficiency is low (less then $1 - M$), most of the captured droplets are reatomized into droplets greater than the critical diameter. Thus a portion of the droplets that were initially less than the critical diameter are converted to droplets greater than the critical diameter by being collected and reatomized. As the capture factor increases, more of these small droplets are captured and reatomized, and this increases the normalized droplet fraction greater than the critical diameter. Shown for illustration in figure 4 are contour plots for cases when all the droplets are initially greater than the critical diameter $(M = 1)$ and for the case when all droplets are initially less than the critical diameter $(M = 0)$.



(a) Generalized three-dimensional contour plot.

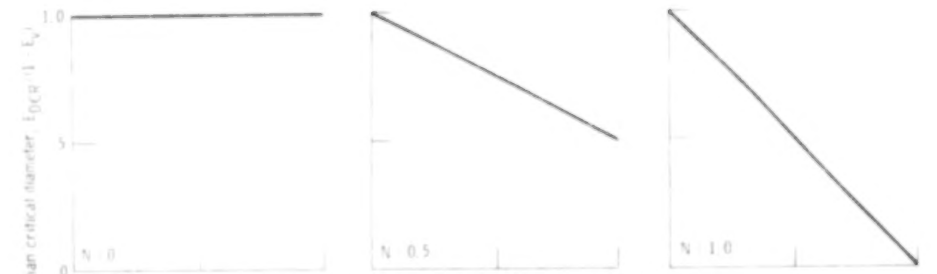


(b) Two-dimensional contour plot, reatomization efficiency, 0.

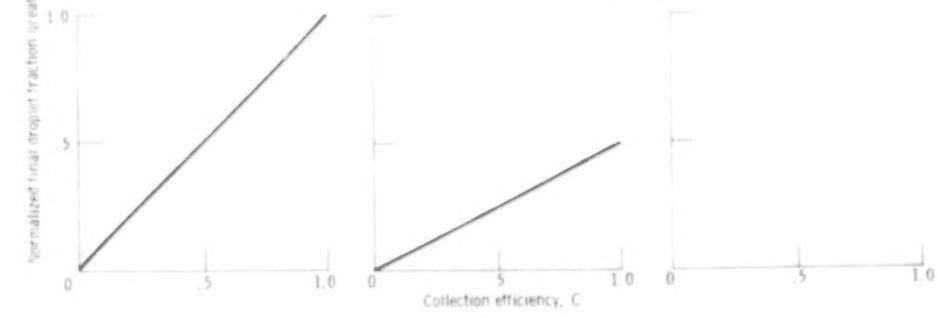
(c) Two-dimensional contour plot, reatomization efficiency, 1 - M.

(d) Two-dimensional contour plot, reatomization efficiency, 1.0.

Figure 3. - Contour plots of interrelationship of flameholder droplet collector factor, C, flameholder reatomization efficiency, N, and the normalized final droplet fraction greater than the critical diameter, $E_{DCR}/(1 - E_v)$, for premixed, partially vaporized mixture with a droplet fraction, M, initially greater than the critical diameter.



(a) All droplets initially greater than the critical diameter.



(b) All droplets initially less than the critical diameter.

Figure 4. - Two-dimensional contour plots of interrelationship of flameholder droplet collection efficiency, C, flameholder reatomization efficiency, N, and the normalized final droplet fraction greater than the critical diameter, $E_{DCR}/(1 - E_v)$, for premixed, partially vaporized mixtures.

Sample Calculation

The procedures developed in the previous sections may be utilized to predict NO_x emissions from lean, premixed, partially vaporized mixtures. The calculations require that combustor operating conditions of temperature, pressure, fuel type, residence time, and equivalence ratio be known. In addition, the initial fuel-air preparation characteristics of droplet size distribution and degree of vaporization are required along with the flameholder blockage and collection and reatomization efficiencies.

To illustrate the methods involved in the application of these procedures, a sample calculation is shown below for the following parameters:

Combustor operating conditions:	
Temperature, K	730
Pressure, MPa	1.3
Fuel type	Jet A
Residence time, msec	2
Equivalence ratio	0.7
Fuel preparation characteristics:	
Degree of vaporization, E	0.7
Fraction of initial droplets greater than critical diameter, M	1.0
Flameholder characteristics:	
Blockage, B, percent	75
Collection efficiency, K	0.5
Reatomization efficiency, N	0.5

The NO_x emissions from lean, premixed, partially vaporized mixtures are determined from equation (3):

$$(NO_x)_{tot} = (1 - E_{DCR})(NO_x)_{\theta_v} + E_{DCR}(NO_x)_{\theta = 1} \quad (3)$$

where the values of $(NO_x)_{\theta_v}$ and $(NO_x)_{\theta = 1}$ are obtained from a stirred reactor analytical model (refs. 20 to 21) and E_{DCR} is determined from equation (7).

$$E_{DCR} = M(1 - E_v)\left(1 - \frac{B}{100}K\right) + (1 - E_v)\left(\frac{B}{100}K\right)(1 - N) \quad (7)$$

Substituting the values for the fuel preparation and flameholder characteristics into equation (7) yields

$$E_{DCR} = (1.0)(1 - 0.7)\left(1 - \frac{75}{100}0.5\right) + (1 - 0.7)\left(\frac{75}{100}0.5\right)(1 - 0.5) = 0.24375$$

and

$$E_v = (1 - E_{DCR}) = 0.75625$$

The pseudovapor phase equivalence ratio, θ_v, is determined from equation (4):

$$\theta_v = (E_v)(\theta) \quad (4)$$

Substituting the pertinent values yields

$$\theta_v = (0.75625)(0.7) = 0.529375$$

Utilizing the stirred reactor analytical model (ref. 24) allows pseudovapor phase equivalence ratio to yield a computed NO_x emission index of 1.35 at the combustor operating conditions. The computed NO_x emission index for stiochiometric combustion at these conditions is 31.5.

Substituting these values into equation (3) yields the total NO_x emissions at these conditions:

$$(NO_x)_{tot} = (0.75625)(1.35) + (0.24375)(31.5) = 8.7 \quad (3)$$

Discussion

As presented previously in the Analysis section, the prediction of NO_x combustion emissions for premixed partially vaporized flows centers on the determination of the fraction of the fuel undergoing combustion that is in the form of droplets greater than the critical diameter. These droplets produce NO_x at stoichiometric conditions. The remaining fuel, whether vaporized fuel or droplets less than the critical diameter (pseudovapor), produces NO_x at conditions corresponding to the vapor phase equivalence ratio. After the various fuel fractions have been determined, the total NO_x for a premixed, partially vaporized flow can be determined by the application of the stirred reactor models at pressure, temperature, equivalence ratio, and residence times corresponding to the desired conditions or by reference to experimental data available for premixed combustion. At present the complex interrelationship of the flameholding device, the aerodynamics, the degree of vaporization, the droplet size distribution and the reatomization process, limits the opportunities for which the final fraction of fuel greater than the critical diameter and the subsequent NO_x emissions can be explicitly computed.

One case that has been experimentally studied is the perforated plate flameholder in a premixed partially vaporized flow. In reference 13, from which the preceeding analytical procedures have been derived and expanded, experimental measurements of the effect of the degree of fuel vaporization on

emissions of oxides of nitrogen were reported. As shown in figure 5 (ref. 13), the magnitude and trends of analytic predictions of the model, agree with measurements of experimental data at various degrees of vaporization, equivalence ratio, and temperature. In this study it was assumed that the perforated plate flameholding device would have a collection efficiency of unity because of the bluff body geometry of the device. Computations of the reatomized droplet size distribution were based on consideration of the film thickness, fuel characteristics, and airflow parameters. Utilization of droplet size correlation equations of reference 27 resulted in a computed reatomized droplet size distribution all less than the critical diameter. Thus, a reatomization efficiency of unity was used since no droplets greater than the critical diameter were computed to exist.

Although, the range of experimental conditions over which NO_x emissions for premixed, partially vaporized mixtures were obtained are certainly limited, the results the analytical procedures show promise of being a useful tool for emissions estimates. Data over a broader range of conditions need to be acquired for premixed, partially vaporized flows to fully establish the limits of applicability of the approach. In particular the influence of flameholder geometry on the liquid droplet collection process and on reatomization needs to be determined to establish a complete predictive capability.

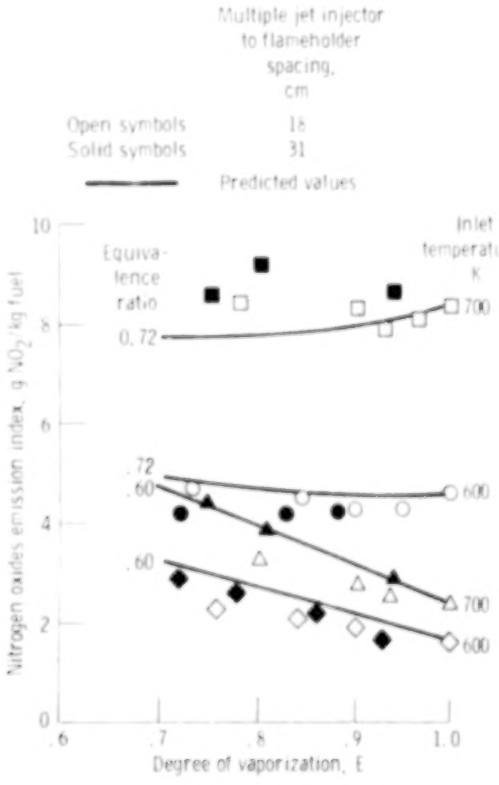


Figure 5. - Comparison of predicted and measured nitrogen oxides emissions index over a range of equivalence ratios, inlet temperatures, and degrees of vaporization. Reference velocity, 35 meters per second; inlet pressure, 0.3 MPa. (From ref. 13)

Parametric Evaluation

An analysis of flameholding devices in lean, premixed, partially vaporized flows has resulted in the development of analytical procedures that can be used to predict oxides of nitrogen emissions. Application of the method to a particular flameholding device is at present constrained by the limited amount of supporting experimental data and by the complexity of the interrelationships of the controlling variables. However, the method can be applied to the parametric evaluation of flameholding device characteristics. The effects of flameholder blockage, collection efficiency, and reatomization efficiency on NO_x emissions for lean, premixed, partially vaporized flows have been computed for Jet A, using the stirred reactor model (ref. 24) to compute pseudovapor phase and stoichiometric NO_x emission indices.

Droplet Reatomization Efficiency

The flameholding device's droplet reatomization efficiency is a function of its ability to reatomize a fuel film of collected liquid droplets into a droplet size distribution. The larger the fraction of the reatomized droplets that are less than the critical droplet diameter, the higher the reatomization efficiency.

Parametrically shown in figure 6 is the effect of the flameholder droplet reatomization efficiency on oxides of nitrogen emissions at conditions representative of an advanced gas turbine aircraft engine cruise point. At a fixed degree of vaporization, as the droplet reatomization efficiency increased, a greater fraction of the reatomized droplets are less than the critical diameter. Since these droplets contribute to the total NO_x emissions as would vapor, rather than as would diffusion flame burning droplets, the total NO_x decreases with increasing reatomization efficiency for fixed degree of vaporization.

Droplet Collection Efficiency

The flameholding device's droplet collection efficiency is a function of its ability to capture the droplets in the premixed, partially vaporized flow.

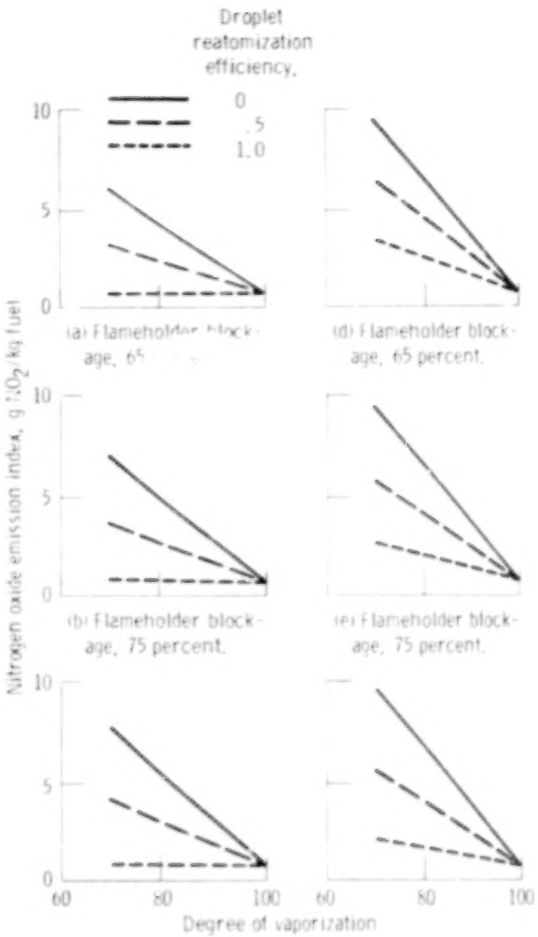


Figure 6. - Effect of flameholder droplet reatomization efficiency on nitrogen oxides emissions index for premixed, partially vaporized mixture over a range of flameholder blockages. Inlet pressure, 1.3 megapascal; inlet temperature, 730 K; residence time, 2 milliseconds; equivalence ratio, 0.5; droplet collection efficiency, 1.0. Parts (a) to (c), all droplets initially less than the critical diameter; (d) to (f) all droplets initially greater than the critical diameter.

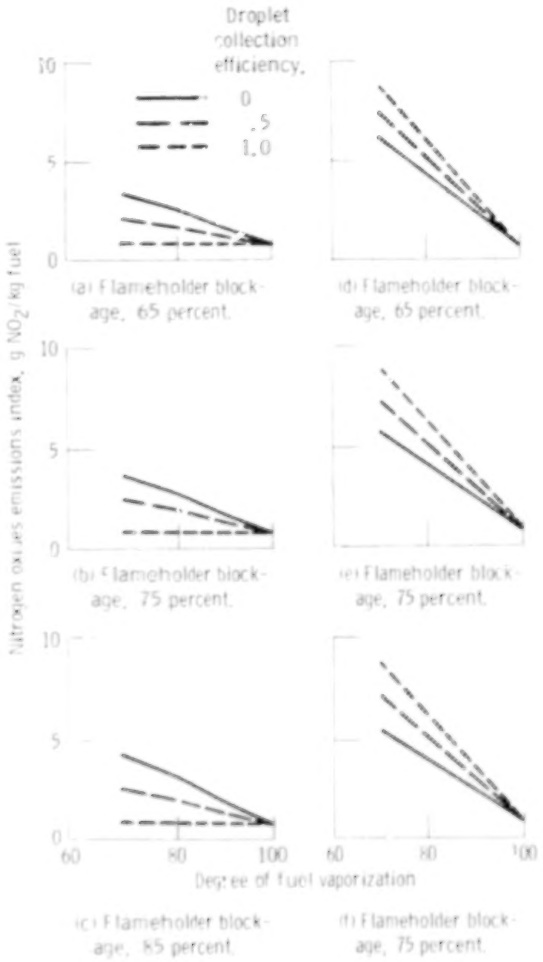


Figure 7. - Effect of flameholder droplet collection efficiency on nitrogen oxides emissions index for premixed, partially vaporized mixtures over a range of flameholder blockages. Inlet pressure, 1.3 megapascals; inlet temperature, 730 K; residence time, 2 milliseconds; equivalence ratio, 0.5; droplet reatomization efficiency, 0.5. Parts (a) to (c), all droplets initially less than the critical diameter; (d) to (f) all droplets initially greater than the critical diameter.

The larger the fraction of droplets within the capture area that actually impact the device, the greater the capture efficiency.

Parametrically shown in figure 7 is the effect of the droplet collection efficiency on oxides of nitrogen emissions at a typical cruise point. The initial drop-size distribution is seen to interact with the droplet collection efficiency. In this particular case the reatomization efficiency is 50 percent. When the initial drop sizes are all initially less than the critical diameter (fig. (7(a) to (c)), increasing the droplet collection efficiency results in increased total NO_x for a fixed degree of vaporization. In these instances, a portion of the droplets that were all less than the critical diameter are reatomized into droplets that are greater than the critical diameter and thus the total NO_x increases. If the reatomization efficiency were 100 percent, the droplet collection efficiency would not have affected the NO_x emissions since no droplets greater than the critical diameter would be created.

When all the initial drop sizes are greater than the critical diameter (fig. 7(d) to (f)), increasing the droplet collection efficiency decreases the NO_x emissions. A portion of the initial droplets are reatomized into droplets less than the critical diameter and hence, lower NO_x emissions. The difference in NO_x levels between 0 and 100 percent collection efficiency will increase as the

reatomization efficiency increases, since a greater portion of the reatomized droplets are less than the critical diameter. Increasing the blockage will also increase the spread in NO_x levels as a greater fraction of the initial droplets are captured for reatomization.

Flameholder Blockage

Shown parametrically in figure 8 is the effect of the blockage or capture area on the emissions of NO_x for typical cruise conditions for a variety of flameholding device collection and reatomization efficiencies. In general, the effect of blockage depends on the initial drop-size distribution. If all the droplets are initially less than the critical diameter, increasing blockage increases the total NO_x emissions at a fixed degree of vaporization, since a greater fraction of the droplets initially less than the critical diameter are collected and then reatomized into droplets greater than the critical diameter. Conversely, when the droplets are all initially greater than the critical diameter, total NO_x emissions decrease with increasing blockage as an increasing portion of the droplets greater than the critical diameter are collected and reatomized into droplets less than the critical diameter. Note that, when the collection efficiency is zero, flameholder blockage has no effect on emissions since no droplets are collected for reatomization.

Equivalence Ratio and Temperature

The previous figures (6 to 8) have been for conditions typical of a cruise point for an advanced aircraft gas turbine. Shown in figure 9 are the effects of equivalence ratio and temperature on NO_x emissions for flameholding devices with 50 percent collection and 50 percent reatomization efficiencies. The behavior presented in this figure parallels that discussed in figure 2. Increasing the inlet temperature or equivalence ratio results in increased NO_x emissions. The behavior of specific temperature-equivalence ratio curves is related to the trade-off between the droplet contribution and vapor contribution to the total NO_x as discussed in the Analysis secton.

In figure 10 various combinations of equivalence ratio and droplet collection and reatomization efficiency, blockage, and initial size are presented for the cruise-point condition. As can be readily observed, a great variety of behaviors can result from the complex interaction of the controlling variables. For example, increasing blockage may either increase or decrease the total NO_x emissions depending on all the above factors. However, general trends for the effect of blockage, collection, and reatomization efficiency on NO_x can be projected, based on the

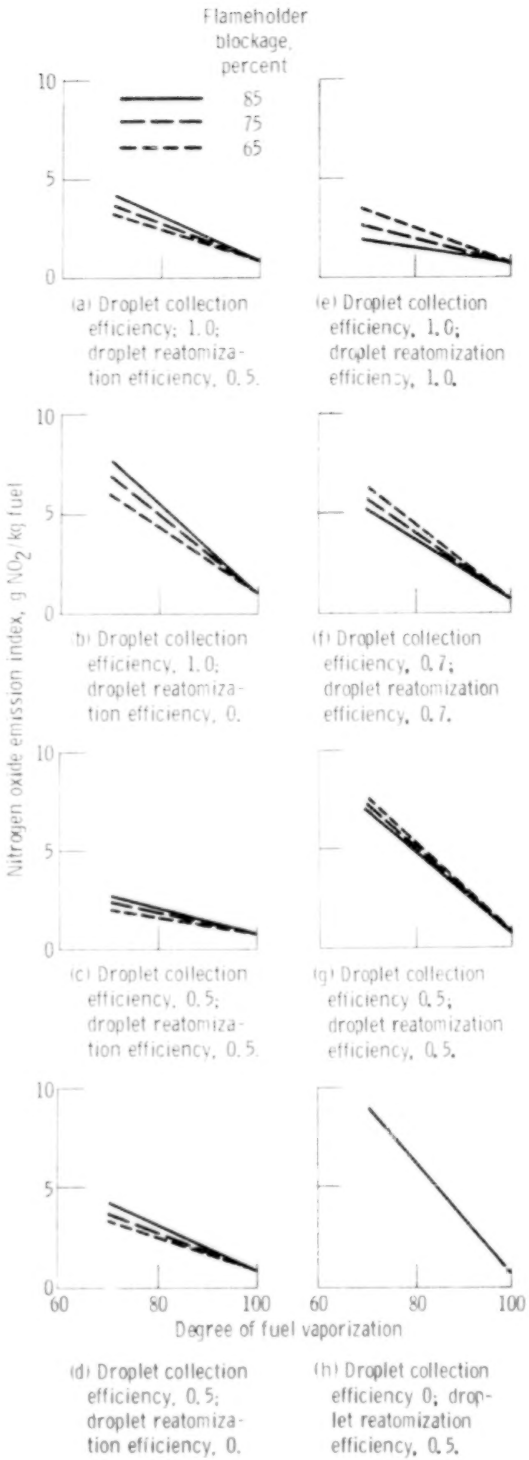

Flameholder blockage, percent
85
75
65
Nitrogen oxide emission index, g NO_2/kg fuel
10
5
0
60
80
100
Degree of fuel vaporization
(a) Droplet collection efficiency, 1.0; droplet reatomization efficiency, 0.5.
(e) Droplet collection efficiency, 1.0; droplet reatomization efficiency, 1.0.
(b) Droplet collection efficiency, 1.0; droplet reatomization efficiency, 0.
(f) Droplet collection efficiency, 0.7; droplet reatomization efficiency, 0.7.
(c) Droplet collection efficiency, 0.5; droplet reatomization efficiency, 0.5.
(g) Droplet collection efficiency 0.5; droplet reatomization efficiency, 0.5.
(d) Droplet collection efficiency, 0.5; droplet reatomization efficiency, 0.
(h) Droplet collection efficiency 0; droplet reatomization efficiency, 0.5.

Figure 8. - Effect of flameholder blockage on nitrogen oxides emission index for premixed, partially vaporized mixtures over a range of flameholder droplet collection and conversion efficiencies. Inlet pressure, 1.3 megapascals; inlet temperature, 730 K; residence time, 2 milliseconds; equivalence ratio, 0.5. Parts (a) to (d), all droplets initially less than the critical diameter; (e) to (h) all droplets initially greater than the critical diameter.

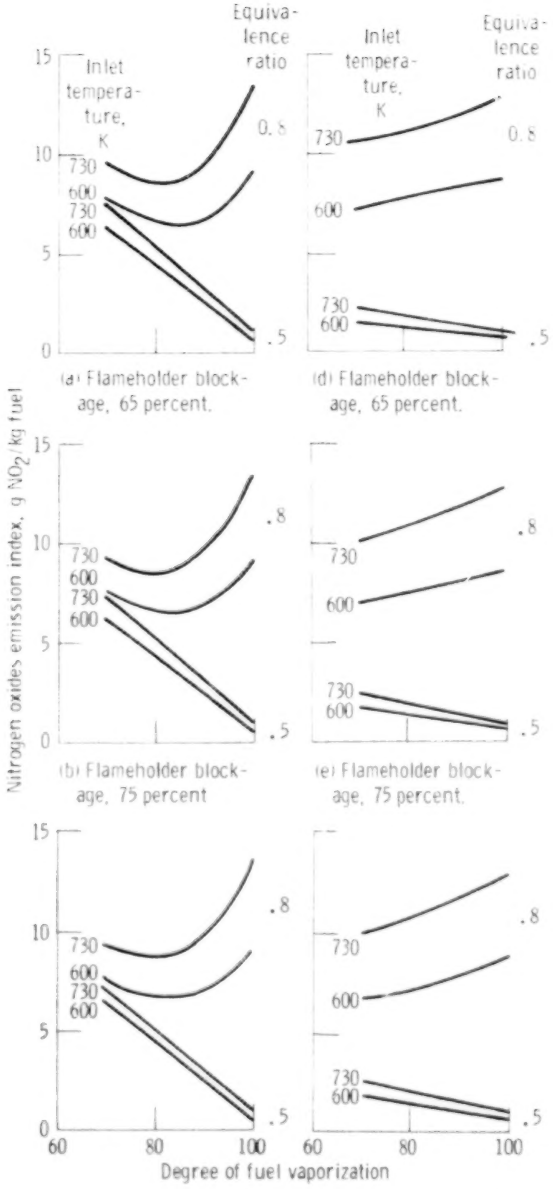

Nitrogen oxides emission index, g NO_2/kg fuel
Inlet temperature, K
Equivalence ratio
Degree of fuel vaporization
(a) Flameholder blockage, 65 percent.
(b) Flameholder blockage, 75 percent.
(c) Flameholder blockage, 85 percent.
(d) Flameholder blockage, 65 percent.
(e) Flameholder blockage, 75 percent.
(f) Flameholder blockage, 85 percent.

Figure 9. - Effect of inlet temperature and equivalence ratio on nitrogen oxides emissions index for premixed, prevaporized mixtures over a range of flameholder blockages. Inlet pressure, 1.3 megapascals; residence time, 2 milliseconds; droplet collection efficiency, 0.5; reatomization efficiency, 0.5. Parts (a) to (c), all droplets initially greater than the critical diameter; (d) to (f), all droplets initially less than the critical diameter.

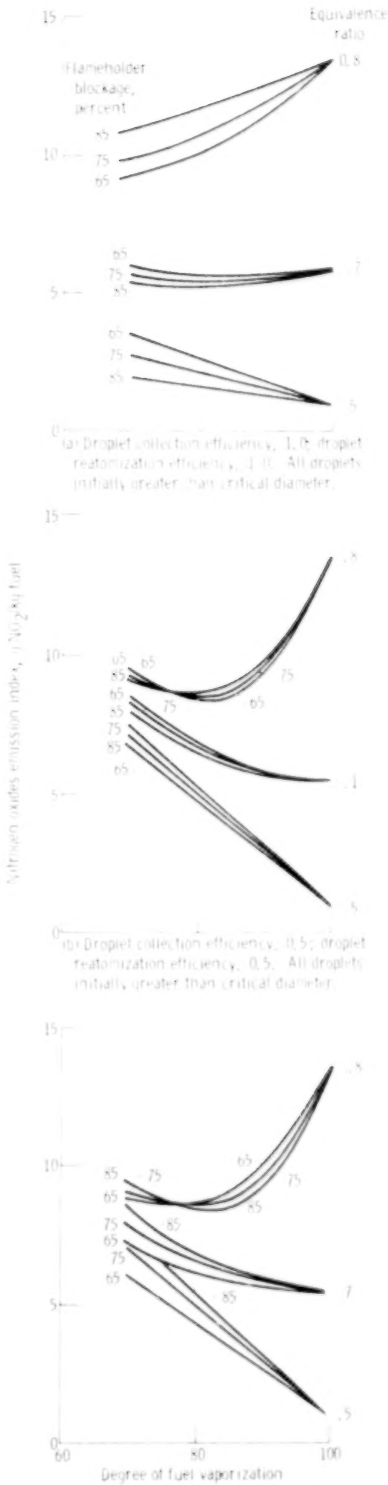

Nitrogen oxides emission index, g NO_2/kg fuel
Flameholder blockage, percent
Equivalence ratio
Degree of fuel vaporization
(a) Droplet collection efficiency, 1.0; droplet reatomization efficiency, 1.0. All droplets initially greater than critical diameter.
(b) Droplet collection efficiency, 0.5; droplet reatomization efficiency, 0.5. All droplets initially greater than critical diameter.
(c) Droplet collection efficiency, 1.0; droplet reatomization efficiency, 0. All droplets initially less than critical diameter.

Figure 10. - Effect of flameholder blockage on nitrogen oxides emission index for premixed, partially vaporized mixtures over a range of flameholder droplet collection efficiencies, droplet reatomization efficiencies, and equivalence ratios. Inlet pressure, 1.3 megapascals; inlet temperature, 730 K; residence time, 2 milliseconds.

pressure, temperature, equivalence ratio, initial dropsize distribution, and degree of vaporization.

When used in this fashion the procedures developed within this report can be a useful guide for the design and optimization of flameholding devices in premixed, partially vaporized flows.

Concluding Remarks

An analysis has been conducted of the effect of flameholding devices on precombustion fuel-air mixture characteristics and on oxides of nitrogen (NO_x) emissions for combustion of premixed, partially vaporized mixtures.

The analysis of the effect on mixture quality of the flameholding device has resulted in a formulation that includes the interrelationships between the flameholder droplet collection efficiency, reatomization efficiency, and blockage and the initial droplet-size distribution. The analysis of the combustion of premixed, partially vaporized mixtures has yielded a procedure to account for the contribution of droplet combustion in partially vaporized mixtures to the NO_x emissions.

The procedures developed in this analysis can be used to predict the NO_x emissions from lean, premixed, partially vaporized mixtures. This calculation requires that the combustor conditions of temperature, pressure, fuel type, equivalence ratio, and residence time be known and that the initial fuel-air preparation characteristics (e.g., droplet size distribution and degree of vaporization) be known from either measurement or calculation. In addition, the interrelationship between the flameholder collection, reatomization, and blockage must be known from either measurement or calculation.

At present the application of these procedures for predicting NO_x emissions are limited by the lack of supporting experimental data, particularly, for computing collection and reatomization characteristics of flameholding devices. The procedures have been applied to analyze a perforated plate flameholder in a premixed partially vaporized mixture with promising results, when compared with the limited experimental data presently available.

The procedures also can be applied to parametrically examine the effect of changes in combustor conditions and flameholding device characteristics. When used in this manner, the procedures can be a useful guide for the design and optimization of flameholding devices for use in premixed, partially vaporized flows.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, October 15, 1980

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16. Abstract

An analysis has been conducted of the effect of flameholding devices on the precombustion fuel-air characteristics and on oxides of nitrogen (NO_x) emissions for combustion of premixed partially vaporized mixtures. The analysis includes the interrelationships of flameholder droplet collection efficiency, reatomization efficiency and blockage, and the initial droplet size distribution and accounts for the contribution of droplet combustion in partially vaporized mixtures to NO_x emissions. Application of the analytical procedures is illustrated and parametric predictions of NO_x emissions are presented.

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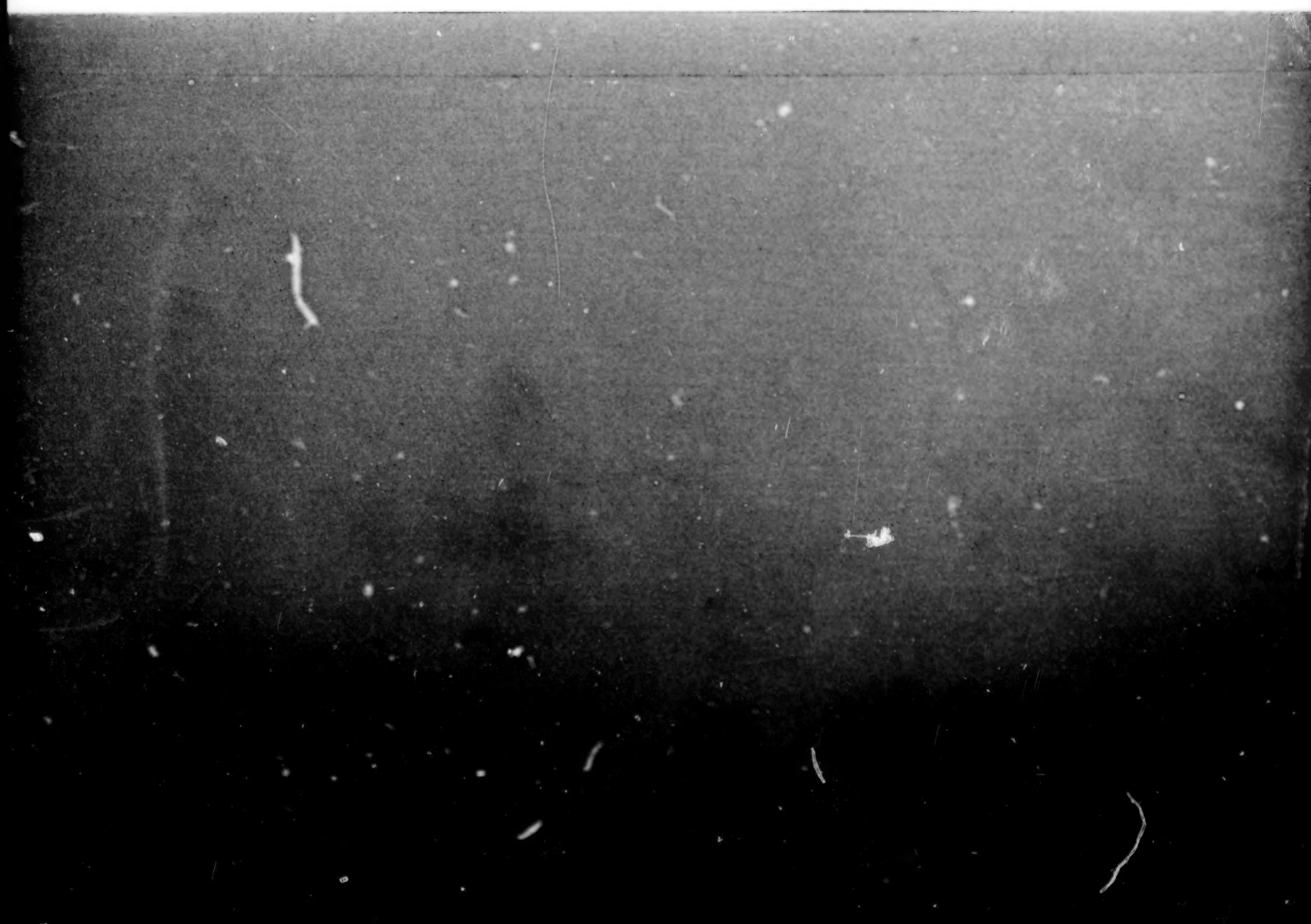

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